ZR Zoological Research

Supplementary Materials

Population size estimates based on GPS telemetry

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SUPPLEMENTARY MATERIALS AND METHODS

STUDY SITES AND SUBJECTS

The study was conducted on Neilingding Island (N22°23′49″–22°25′35″, E113°46′18″–113°49′49″), an enclosed island located on the east side of the Pearl River port in Guangdong Province, China, with a total area of 4.98 km^2 and highest elevation of 340.9 m. The Neilingding Nature Reserve was established in 1984 to protect the island ecosystem and several key animal species, including the resident rhesus macaques. The island falls within a subtropical monsoon climate, characterized by an average annual temperature of 22.0 ℃ and annual precipitation of 1 926.9–1 975.1 mm. The area contains typical subtropical evergreen broad-leaved forest, although the primary vegetation type has been transformed by local anthropogenic activities. Since the establishment of the nature reserve, vegetation restoration has occurred rapidly, although remnants of human influence, such as construction debris and traces of agricultural vegetation, are still visible in the landscape (Zhang et al., 2021).

The macaque population on the island was first documented in the late 1970s. Subsequent to the establishment of the nature reserve, several census studies were undertaken, based upon which the population increased from 200 macaques in 1984 (Wang et al., 1999) to ca. 1 000 individuals in 2016 (Chu et al., 2019).

GPS COLLAR DEPLOYMENT

The GPS collars were attached to the target macaques during two time periods. The first collaring phase occurred from December 2019 to July 2020, with a delay due to the impact of COVID-19. During this period, a preliminary survey of macaque distribution was conducted alongside the island road, leading to the collaring of 17 individuals. Given the potential influence of individual factors, such as sex, reproductive status, and social rank, on spatial utilization through nutritional requirements or resource occupancy (Mace & Harvey, 1983), we aimed to attach GPS collars on 4–5 individuals, including two adult males and 2–3 adult females, in each group depending on group structure. The second collaring phase occurred from January to April 2022, leading to the collaring of 27 individuals. However, due to the low habituation of some groups, only 1–2 GPS collars were successfully deployed in these groups. Over the study period, six collars detached, including one collar that detached twice; each collar was reassigned to a different individual after recovery. In total, 44 collars were deployed and 51 individuals were tracked. Group affiliations were deduced from home range boundaries derived from collar location fixes, validated by consistent individual home ranges within the same group and on group size surveys. Given the extended study period and 1–2 year operational/battery lifespan of the collars, which resulted in less fixes acquired for the collars deployed during the first period (December 2019 to July 2020), a specific timeframe (May 2021 to April 2022) was selected during which 32 collars from nine groups accumulated sufficient data for analysis.

A pipe with an anesthetic needle was used to dart and anesthetize the macaques using Zoletil 50 (Virbac, France) with the assistance or following the guidelines of veterinarians from Guangzhou Zoo. All macaques were released at the place they were caught, and their health was monitored continuously till they recovered. No macaque was injured or died during this process.

DATA COLLECTION AND DATA TIDE

HQXSN40S GPS collars (Hunan Global Messenger Technology, Hunan, China) were used to track the individual macaques. The collars were marked with an ID to help identify the individual

wearing the collar. The collars recorded spatial and temporal data with each fix, including date, time, latitude-longitude position, altitude, and accuracy indexes such as number of satellites, horizontal dilution of precision (HDOP), and vertical dilution of precision (VDOP). The collars were programmed to record 13 hourly positions from 7:00 to 19:00 every day to cover the daily activity range of the macaques and maximize battery life. All recorded coordinates were in WGS84 format and later transformed to WGS84 UTM Zone 49N for subsequent analysis. Given the potential for inadequate collar performance resulting in missing or delay of location, as well as errors in successfully acquired fixes (D'Eon et al., 2002; Frair et al., 2004). A strict screening protocol was employed. Initially, fixes with HDOP values ≥4 were excluded (Lewis et al., 2007; Sanchez-Giraldo and Daza, 2019).Additionally, fixes not aligning with macaque movement characteristics, such as sharp turning angle greater than 178° or less than – 178°, were excluded (Bjørneraas et al., 2010).

GROUP SIZE SURVEY

During the study period, focal group field observations were conducted to obtain group size data. Tracked groups were enticed to an open groundusing bait (e.g., corn and peanuts), with the number of individuals in different sex-age categories within each group then counted. To prevent attracting more than one group to the provisioning site, provisioning usually occurred within the core area of each group. When neighboring groups visited the same provisioning site, members of different groups always fed in turn and did not feed at the same time. When difficulties arose in distinguishing group identity for individuals, repeated surveys of the same group were conducted to ensure accuracy. Wandering males affiliated to a group were also counted. Such males were often of lower ranked, exhibited minimal interactions with individuals in the group, and refrained from feeding on the provisioned food when the alpha male and other higher-ranking individuals were feeding, but they followed the travel direction of the group. For each group, group counting was repeated 2–4 times in a single survey to ensure accuracy. The reproductive status and relative social rank of each collared individual were also recorded during the field observations. Relative social rank was defined based on the priority order of feeding, with higher-ranked individuals being those with precedence or the capacity to monopolize food resources. Notably, as the survey occurred within the home range boundary and each group survey lasted less than an hour – thus affecting only one or two fixes – provisioning was deemed negligible in terms of home range estimation impact. The nine groups underwent three group size surveys, specifically in August 2021, March 2022, and August 2022 (except for group SP in August 2022 due to limited habituation). Given that the largest exclusive ratio occurred in March 2022, group size data from that month were adopted for population estimation. Group size results are shown in Supplementary Table S1.

HOME RANGE ESTIMATES

Home range was estimated using kernel density estimates (KDE), a well-established technique that uses non-parametric estimates of the spatial distribution of fixes to estimate home range (Kernohan et al., 2001). The method entails smoothing a two-dimensional distribution histogram of fixes to obtain the probability density distribution of an animal's spatial utilization. Smoothing parameter h transforms the histogram into the probability density distribution curve and home ranges are estimated based on 95% isopleths. The KDE approach generates the probability density distribution of an animal's spatial utilization and evaluates utilization intensity. Here, we determined smoothing parameter h_{ref} based on the covariance of the fix coordinates and sample size (fix number was used to estimate home range), which was used to calculate the smooth home range boundary

without producing discrete home range patches. Home ranges for each group were calculated using the fixes of all tracked individuals belonging to the group (Supplementary Table S2). Home range estimates were calculated in R 4.2.0 with the "adehabitatHR" package (Calenge, 2006).

POPULATION ESTIMATES

The number of groups on the island was estimated based on the home range area and overlap of the study groups. A simple method was adopted to avoid the impact of home range overlap on population estimation. First, the "terra" package (Hijmans, 2022) was used to calculate the complete exclusive area (A_{ex}) of each group, i.e., area that did not overlap with any other group. The "exclusive ratio" was then calculated, i.e., ratio of the complete exclusive area to the home range area for each month.

$$p_{ex} = \frac{A_{ex}}{A_{total}} \quad \#(1)$$

The month with the highest exclusive ratio (p_{ex}) was selected to estimate population size, as a low exclusive ratio may lead to an overestimation of population size. The complete exclusive area of the island (A_t) was subsequently determined.

$$A_t = A_s \times \frac{\sum_{i=1}^{n} A_{ex_i}}{A_{sa}} \quad \#(2)$$

where A_{sa} is the total area of the home range of the nine groups, A_{ex_i} is the complete exclusive area of group i, and A_s is the habitat area of the island. Finally, the number of groups was calculated by dividing A_t by the mean exclusive area of the nine groups $\overline{A_{ex}}$. Population size N was calculated by multiplying the group number and mean group size n obtained in the group size survey.

$$N = n \times \frac{A_t}{\overline{A_{ex}}} \#（3）$$

UTILIZATION DISTRIBUTION SIMILARITY

To determine if the utilization pattern of one individual can represent the home range utilization pattern of the whole group, we compared the utilization distribution (UD) similarity of each individual and their group using an overlap index, Bhattacharyya's affinity (BA), a statistical measure of affinity between two populations (Bhattacharyya, 1943). Compared to traditional methods, this measure not only quantifies home range overlap but also the similarity in utilization intensity at a specific location (Fieberg & Kochanny, 2005). The BA index ranges from zero (no overlap) to one (identical UDs). The UD of each individual was compared to the UD of their group to yield a BA value. A predefined threshold of 0.95 was employed to indicate similarity. When the BA value exceeded 0.95, it indicated the feasibility of inferring a group's home range utilization pattern based on the individual's utilization pattern. Group WGJ was not included as only one individual was collared. UD similarity was calculated using the "adehabitatHR" package.

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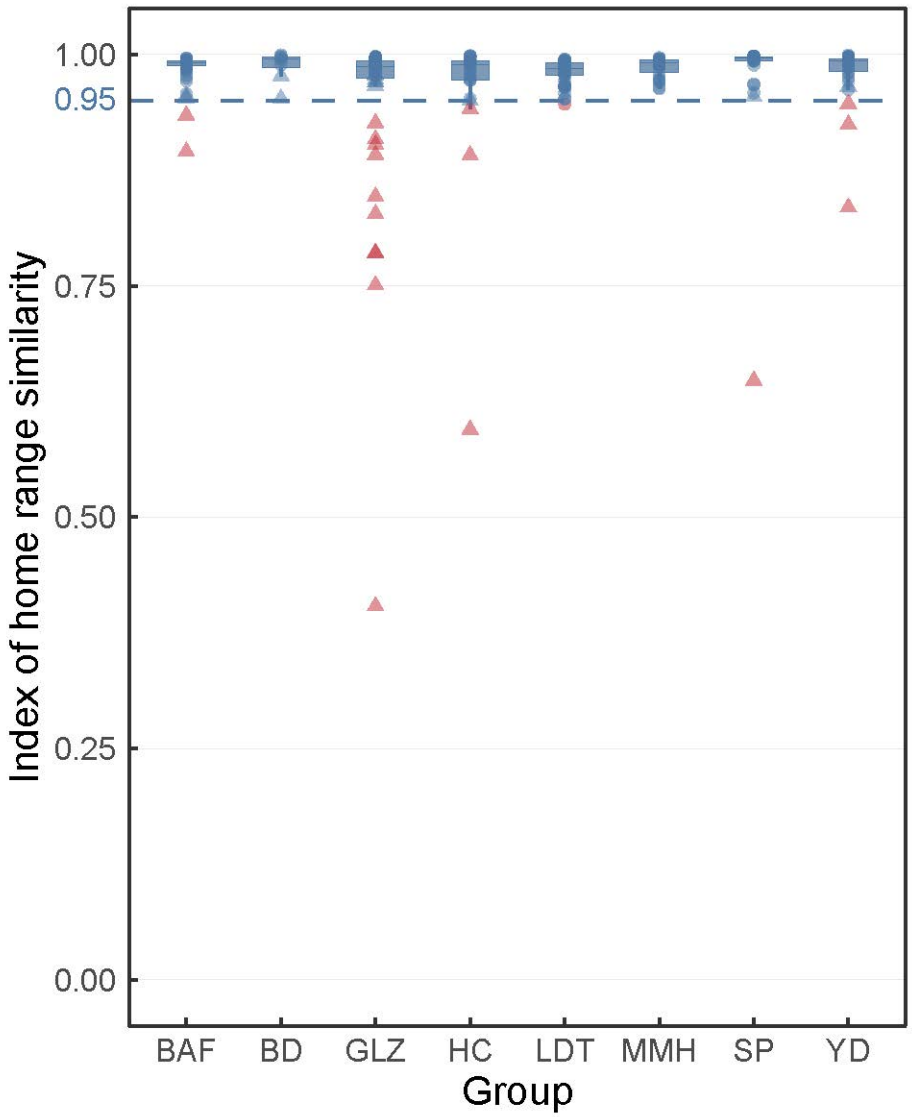

Supplementary Figure S1 Boxplot of BA distribution among eight rhesus macaque groups on Neilingding Island, Guangdong, China

Each point represents the UD similarity level between a single individual and its group. Points above the horizontal line (0.95) show high similarity to the group. BA values lower than 0.95 are marked in red, and BA values calculated with less than 100 fixes are shown in triangles.

Supplementary Table S1 | Group structure of nine rhesus macaques on Neilingding Island.

Group ID	Survey Time	Adult Male	Adult Female	Sub-adult Male	Sub-adult Female	3-4a	2a	1a	Infant	Group Size
BD	2022.8	5	5			2	2	3	2	19
	2022.3	2	5			1	2	2	2	14
	2021.8	3	6			2	2	2	3	18
BAF	2022.8	4	7			1	4	5	3	24
	2022.3	4	7			1	2	4	5	23
	2021.8	4	7			1	3	7	4	26
GLZ	2022.8	5	10		1	1	3	6	8	33
	2022.3	4	9			3	2	5	2	25
	2021.8	5	8			1	3	7	4	28
HC	2022.8	3	13			4	4	6	11	41
	2022.3	4	13			4	5	7	6	41
	2021.8	3	12	2	3	5	3	9	7	44
LDT	2022.8	5	8			2	4	4	5	28
	2022.3	5	8			3	2	5	2	25
	2021.8	4	8			3	2	6	3	26
MMH	2022.8	5	8			2	4	5	4	25
	2022.3	3	7				2	5	4	21
	2021.8	3	7		1	2	3	5	4	25
SP	2022.3	3	9	1		2	3	6	5	29
	2021.8	5	7			2	3	4	4	25

Group ID	Survey Time	Adult Male	Adult Female	Sub-adult Male	Sub-adult Female	3-4a	2a	1a	Infant	Group Size
WGJ	2022.8	5	7			1	3	5	5	26
	2022.3	5	6	2		2	2	5	6	28
	2021.8	3	5	3		2	5	7	2	27
YD	2022.8	4	10			2	3	6	6	31
	2022.3	5	10			1	2	5	7	31
	2021.8	3	12		2	2	3	7	3	32

Supplementary Table S2 Individual data acquisition and screening of nine rhesus macaque groups on Neilingding Island

Group ID	Individual ID	Monitoring time	Fixes amount	Screening fixes amount	Ratio of valid fixes
BAF	007	2021/05/01-2022/04/30	4 711	3 778	80.20%
	024	2021/05/01-2022/04/14	3 493	2 064	59.09%
	025	2021/05/01-2022/04/30	5 112	3 778	73.90%
	033	2021/05/01-2022/04/30	4 968	3 849	77.48%
	040	2021/05/01-2022/04/30	4 643	3 950	85.07%
BD	023	2021/05/01-2021/07/14	1,281	577	45.04%
	030	2021/05/01-2022/04/30	4 712	3 825	81.18%
	047	2021/05/01-2022/04/30	2 003	1 218	60.81%
	029c	2022/03/30-2022/04/30	469	362	77.19%
GLZ	004	2021/05/01-2022/04/30	1,651	1 112	67.35%
	005	2021/05/01-2022/04/30	1 772	1 134	64.00%
	012	2021/05/01-2022/04/30	4 720	3 522	74.62%
	013	2021/05/01-2022/04/30	3 957	2 464	62.27%
	036	2021/05/01-2022/04/30	3 712	1 957	52.72%
HC	001	2021/05/01-2022/04/30	4 711	3 274	69.50%
	032	2021/05/01-2022/04/30	4 194	1 928	45.97%
LDT	017	2021/05/01-2022/04/30	4 722	3 703	78.42%
	026	2021/05/01-2022/04/30	4 868	4 054	83.28%
	027	2021/05/01-2022/04/30	4 701	3 923	83.45%
	044	2021/05/01-2022/04/30	4 711	4 155	88.20%
	014a	2021/05/01-2022/06/28	763	610	79.95%
MMH	037	2021/05/01-2022/04/30	4 716	4 088	86.68%
	014b	2021/8/11-2022/04/30	3 589	2 855	79.55%
	035a	2021/05/01-2021/08/26	1 625	1 252	77.05%
	035b	2021/08/16-2022/04/30	461	357	77.44%
SP	042	2021/05/01-2022/04/30	3 102	2 581	83.20%
	043	2021/05/01-2022/04/30	4 781	4 057	84.86%
	041a	2021/05/01-2021/05/17	162	97	59.88%
	041b	2021/08/10-2022/04/30	3 421	2 814	82.26%
WGJ	039	2021/05/01-2022/04/30	4 728	3 841	81.24%
YD	048	2021/05/01-2022/04/30	3 242	2 508	77.36%
	049	2021/05/01-2022/04/30	4 732	4 003	84.59%
	029b	2021/05/01-2022/02/22	4 020	3 207	79.78%
All individuals			114 453	86 897	75.92%

Supplementary Table S3 Monthly home range attribute of nine rhesus macaque groups on Neilingding Island

Month	Group	Home range size (ha)	Exclusive ratio(%)
2021_05	BAF	27.2144	31.84%
2021_05	BD	23.41558	12.56%
2021_05	GLZ	18.98972	0.17%
2021_05	HC	48.24373	43.29%
2021_05	LDT	10.75586	23.49%
2021_05	MMH	19.13011	55.51%
2021_05	SP	18.88144	16.44%
2021_05	WGJ	30.046	63.62%
2021_05	YD	26.86899	34.10%
2021_06	BAF	29.34498	0.11%
2021_06	BD	16.56254	17.07%
2021_06	GLZ	58.89677	23.85%
2021_06	HC	33.88699	58.72%
2021_06	LDT	10.86048	27.06%
2021_06	MMH	16.28623	36.75%
2021_06	SP	20.68023	6.20%
2021_06	WGJ	24.06015	59.97%
2021_06	YD	20.1222	65.19%
2021_07	BAF	34.27956	10.73%
2021_07	BD	23.80351	15.53%
2021_07	GLZ	52.19157	11.86%
2021_07	HC	72.9388	40.96%
2021_07	LDT	16.41394	7.35%
2021_07	MMH	24.091	43.88%
2021_07	SP	20.9861	7.55%
2021_07	WGJ	46.53377	62.52%
2021_07	YD	26.10205	15.92%
2021_08	BAF	26.97554	3.61%
2021_08	BD	42.20764	25.26%
2021_08	GLZ	45.23979	30.45%
2021_08	HC	57.26111	37.61%
2021_08	LDT	14.21091	22.52%
2021_08	MMH	31.77633	50.54%
2021_08	SP	19.09099	0.00%
2021_08	WGJ	30.88466	50.21%
2021_08	YD	43.96287	35.81%
2021_09	BAF	29.52887	0.54%
2021_09	BD	20.49692	17.00%
2021_09	GLZ	46.85239	48.25%
2021_09	HC	57.48772	45.72%
2021_09	LDT	12.68764	19.49%

Month	Group	Home range size (ha)	Exclusive ratio(%)
2021_09	MMH	16.60341	40.88%
2021_09	SP	19.06148	12.34%
2021_09	WGJ	18.6486	55.50%
2021_09	YD	33.05877	27.10%
2021_10	BAF	26.33952	0.82%
2021_10	BD	18.03691	5.26%
2021_10	GLZ	58.99777	53.83%
2021_10	HC	53.53535	31.78%
2021_10	LDT	12.85539	4.64%
2021_10	MMH	15.82655	46.93%
2021_10	SP	14.81125	6.47%
2021_10	WGJ	14.8227	38.95%
2021_10	YD	30.09705	23.34%
2021_11	BAF	21.92946	0.00%
2021_11	BD	9.780909	8.01%
2021_11	GLZ	62.54151	56.78%
2021_11	HC	57.29252	38.40%
2021_11	LDT	13.43522	0.00%
2021_11	MMH	18.15747	42.09%
2021_11	SP	13.36225	5.24%
2021_11	WGJ	15.40052	43.27%
2021_11	YD	25.70479	24.05%
2021_12	BAF	31.58293	8.77%
2021_12	BD	13.23508	8.99%
2021_12	GLZ	49.57942	42.50%
2021_12	HC	47.24137	44.24%
2021_12	LDT	14.15825	15.90%
2021_12	MMH	25.20452	40.31%
2021_12	SP	20.82297	19.28%
2021_12	WGJ	10.91948	48.40%
2021_12	YD	19.07664	25.13%
2022_01	BAF	19.04569	9.00%
2022_01	BD	15.30632	6.50%
2022_01	GLZ	42.58659	52.43%
2022_01	HC	37.02531	55.51%
2022_01	LDT	12.19796	37.64%
2022_01	MMH	31.91675	43.27%
2022_01	SP	14.57494	26.34%
2022_01	WGJ	13.27559	63.08%
2022_01	YD	19.60574	35.78%
2022_02	BAF	19.37018	11.79%
2022_02	BD	13.87557	23.16%
2022_02	GLZ	41.51598	58.12%

Month	Group	Home range size (ha)	Exclusive ratio(%)
2022_02	HC	21.91335	62.60%
2022_02	LDT	10.77977	68.69%
2022_02	MMH	19.78021	51.86%
2022_02	SP	14.48304	45.11%
2022_02	WGJ	14.40582	60.96%
2022_02	YD	21.96352	38.51%
2022_03	BAF	26.10083	30.63%
2022_03	BD	15.06129	25.54%
2022_03	GLZ	25.5213	40.72%
2022_03	HC	19.67188	73.12%
2022_03	LDT	11.53956	82.90%
2022_03	MMH	22.99794	65.16%
2022_03	SP	14.87574	37.14%
2022_03	WGJ	11.98567	83.06%
2022_03	YD	22.17637	58.59%
2022_04	BAF	16.29786	6.20%
2022_04	BD	18.29186	18.46%
2022_04	GLZ	24.77384	64.32%
2022_04	HC	26.76797	70.43%
2022_04	LDT	13.07166	57.48%
2022_04	MMH	19.41701	71.67%
2022_04	SP	10.77218	15.77%
2022_04	WGJ	16.46277	71.97%
2022_04	YD	18.61773	52.05%